NEGATIVE-POLARITY ROD-PINCH DIODE EXPERIMENT AT 5 MV ON RITS-3*

G. Cooperstein[+], F.C. Young[++], R.J. Commisso, D.D. Hinshelwood, D. Mosher[++], P.F. Ottinger J.W. Schumer, S.J. Stephanakis[++], S.B. Swanekamp[++], and B.V. Weber

Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA

S. Portillo, I. Molina

Sandia National Laboratories, Albuquerque, NM 87185 USA

S.G. Clough

AWE, Aldermaston, UK

Abstract

Recent theoretical modeling of rod-pinch (RP) diode behavior has been carried out for diode voltages of up to 10 MV.[1] The theory, consistent with experimental results on Asterix at up to 6 MV [2], predicts that, above 4 MV, x-ray production in the forward direction is more efficient for negative-polarity operation than positive-polarity operation. Here we report on negative-polarity RP diode experiments at 5 MV on RITS-3 [3], an inductive-voltage-adder (IVA) generator with vacuum flowing electrons. Extensive analysis of the electrical and x-ray data combined with numerical simulation suggests that the diode operation is consistent with the modeling.

I. INTRODUCTION

The RP diode has been extensively studied as a radiographic source on positive-polarity generators from 0.5 to 6 MV [4-6]. Positive-polarity operation, illustrated in Fig. 1a, optimizes electron flow to the anode rod by minimizing anode emission surfaces that can lead to extraneous electron losses. Below 4 MV, the electron angular distribution at the rod tip allows for efficient radiation production in the forward direction (0°). Experiments on Asterix in positive polarity at 4-6 MV [2] and related numerical simulations [6] suggest that 1.4 - 2 times more radiation is produced in the backward direction because most of the electrons approach the tapered anode at angles close to 180° along the magnetic field null. At higher voltages, the radiation distribution is more strongly coupled to the electron angles-of-incidence; thus higher x-ray yield in the forward direction requires a more challenging [7] negative-polarity geometry (see Fig. 1b) for voltages above 4 MV. Experiments at AWE have successfully investigated reentrant negative-polarity RP geometries below 3 MV [8].

Results from negative-polarity RP experiments at 5 MV on RITS-3 are given in this paper. The purpose of these experiments was to study the power-flow between an IVA generator with vacuum flowing electrons and a RP diode in negative polarity, and to provide an independent confirmation of the theoretical predictions. These experiments were made in preparation for more extensive research and development of this diode geometry on the new 6-MV, 360-kA, 50-ns Mercury IVA pulsed-power generator [9]. Extensive analysis of the electrical and x-ray data combined with numerical simulation suggests that the diode performed as predicted in [1]. However, to avoid late-time impedance collapse due to possible parallel electron paths, the data suggest that it is important to confine ion production to the diode region. This can be accomplished by ensuring that power-flow electrons from the IVA are benignly dumped at large diameter and by achieving critical current early in the pulse so that diode electrons do not turn on ions along the anode feed.

II. EXPERIMENTAL ARRANGEMENT

The geometry of the diode is shown in Fig. 2a. A non-emitting knob that held the RP anode hardware diverts vacuum-flowing electrons from the upstream MITL radially out to harmlessly hit the vacuum chamber outer wall (66-cm diam). In total there were two short-circuit

* Work supported in part by the US NNSA through SNL, and by the UK AWE.

[+] email: cooperstein@nrl.navy.mil

[++] Titan, Reston, VA 20190 USA.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005	**N/A**	**-**

4. TITLE AND SUBTITLE
Negative-Polarity Rod-Pinch Diode Experiment At 5 Mv On Rits-3

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013.

14. ABSTRACT
Recent theoretical modeling of rod-pinch (RP) diode behavior has been carried out for diode voltages of up to 10 MV.[1] The theory, consistent with experimental results on Asterix at up to 6 MV [2], predicts that, above 4 MV, x-ray production in the forward direction is more efficient for negative-polarity operation than positivepolarity operation. Here we report on negative-polarity RP diode experiments at 5 MV on RITS-3 [3], an inductive-voltage-adder (IVA) generator with vacuum flowing electrons. Extensive analysis of the electrical and x-ray data combined with numerical simulation suggests that the diode operation is consistent with the modeling.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

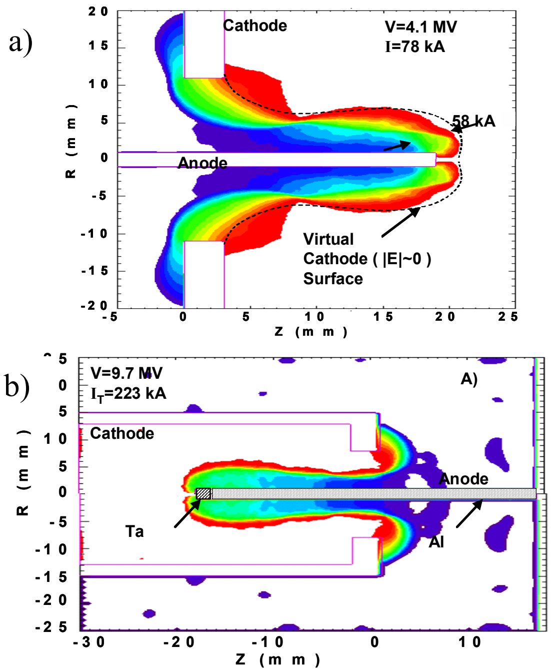

Figure 1. PIC simulations showing current flow contours for **a)** positive-polarity rod-pinch diode and **b)** negative-polarity reentrant rod-pinch diode

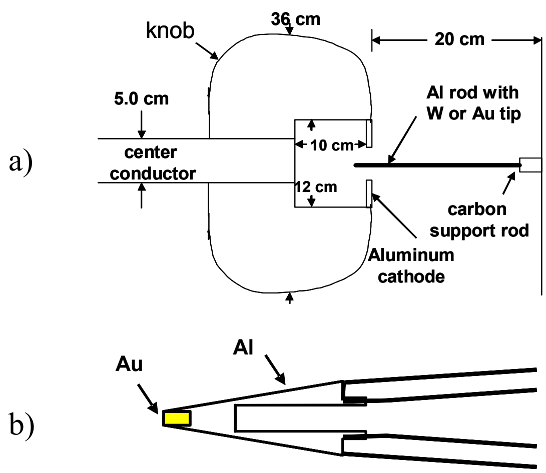

Figure 2. Negative-polarity reentrant rod-pinch diode on RITS-3 showing **a)** the composite-anode geometry, and **b)** the hollow Al anode cone with Au tip geometry.

calibration shots, nine composite-anode shots and three hollow-cone anode shots. For simplicity, only three shots will be described in detail here. Two composite-anode shots used a 3-mm OD (= $2R_A$), 1.6-mm ID, 20-cm long Al tube that was either terminated with a 2-mm diam, 3-mm long Au rod (shot 621) or a 2-mm diam, 5-cm long W rod (shot 623). Shot 621 had an 18-mm cathode radius, R_C, with R_C/R_A = 12, and shot 623 had R_C = 9 mm with R_C/R_A = 9. The third shot, 625, used a hollow-cone Al anode, shown in Fig. 2b, with a 1.5-mm wall thickness, an 8° (full) internal angle to minimize downstream x-ray absorption, and a 1-mm diam, 2-mm long Au tip. R_A = 3 mm at the cathode position, R_C = 20 mm, and the tip extends 12 mm inside the cathode plane.

Diode voltage was inferred from upstream anode and cathode current monitors using the Mendel formula [10] to calculate the voltage at that position and then using a transmission-line correction followed by an inductive correction for the rod geometry. Diode current was measured with a 15-cm radius Rogowski coil on the downstream anode plane. This current was consistent with B-dot measurements made within 3 cm of the anode rod suggesting that the knob did not emit and prevented vacuum-flowing electrons from the upstream MITL from hitting the downstream anode plate. A scintillator-photodiode was used to measure the x-ray pulse shape; arrays of TLDs were used to determine x-ray angular distributions; and a tungsten (W) rolled edge was used to determine the x-ray spot size.

PIC code calculations of the experimental geometry, shown in Figs. 3a and b, suggested that the RP diode with R_C/R_A = 10 would operate at about 53 Ω at 4.5 MV with about 25% of the current lost to protons when proton production was restricted to the region bounded by the anode tip and one AK gap outside of the cathode cavity. This would be a good match to the 44 Ω self-limited impedance of the RITS-3 MITL. When proton production was allowed along the entire 20-cm length of the anode feed, significant impedance collapse occurred.

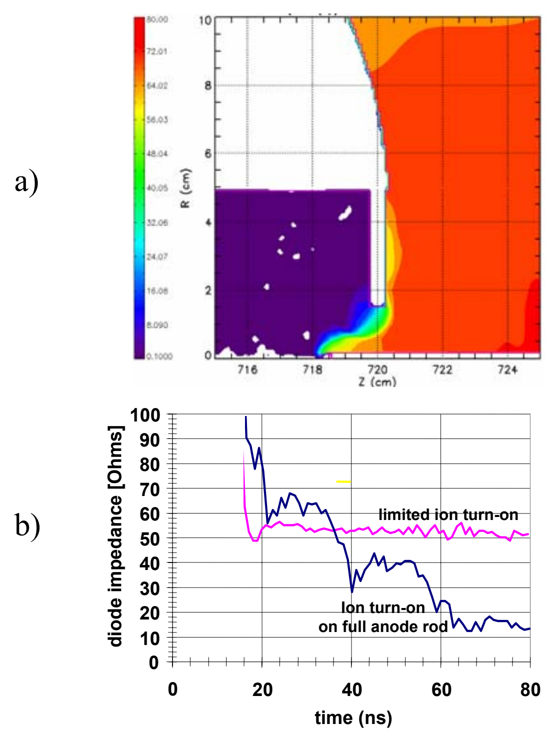

Figure 3a. PIC code calculation showing current flow contours for a negative-polarity reentrant rod-pinch diode geometry on RITS3. **3b.** Diode impedance with non-limited and limited ion turn-on for R_C/R_A = 10.

III. RESULTS AND CONCLUSIONS

The corrected diode voltage (V), current (I), x-ray photodiode signal (PD) and calculated IV^2 are shown in Fig. 4a for shot 621 and Fig. 4b for shot 623. Shot 621 exhibited a shorter radiation pulse (21 ns FWHM) and lower dose (40 rad @ 1 m) compared with shot 623 (41 ns FWHM and 80 rad @ 1 m). The doses were measured at 20° off axis to avoid x-ray self-absorption. The shorter pulse width and smaller dose of shot 621 with a 3-mm long Au tip occurs because the pinch takes longer to form on the Al anode rod and the impedance collapses earlier in time due to a possible parallel electron path to the anode feed aided by ions as suggested in the PIC code calculations of Fig. 3b. Recent experiments reported on Asterix in negative polarity did not exhibit impedance collapse with diode geometries similar to shot 621 [11]. However, Asterix has a slower risetime and larger prepulse than RITS-3 which could have led to earlier anode ion turn-on opposite the cathode, which is what the 5-cm long W insert accomplished on shot 623.

A large linear array of TLDs confirmed that the dose scales as the inverse square with distance from the tip of the rod, which suggests that x-ray emission from electrons hitting the back anode plate is minimal and did not interfere with the dose measurements. The measured dose for shot 623 is consistent with PIC code predictions for these beam parameters. In addition, the x-ray angular distribution for shot 623, measured with an array of TLDs, is also consistent with most of the electrons hitting the anode rod in the backward direction as illustrated in Fig. 1. This measured distribution for shot 623, and a similar shot 616, are shown in Fig. 5 along with a theoretical ITS [12] calculation (axial injection) that confirms the strong fall-off at 0° due to x-ray self-absorption primarily from the 5-cm long W insert. If electrons had hit the anode rod primarily in the radial direction, the predicted dose would have been significantly reduced in the forward direction and would have increased rather than decreased at larger angles as illustrated in Fig. 5 (radial injection).

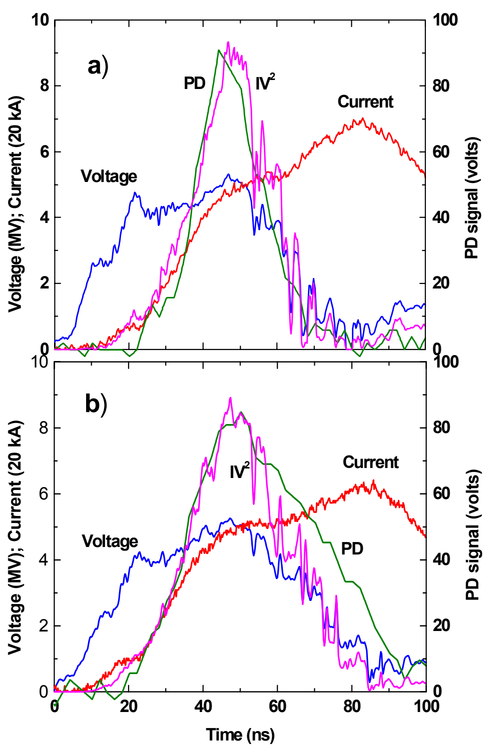

Figure 4. Diode voltage (V), current (I), x-ray photodiode signal (PD) and IV^2 for **a)** shot 621 with 3-mm long Au tip and **b)** shot 623 with 5-cm long W insert.

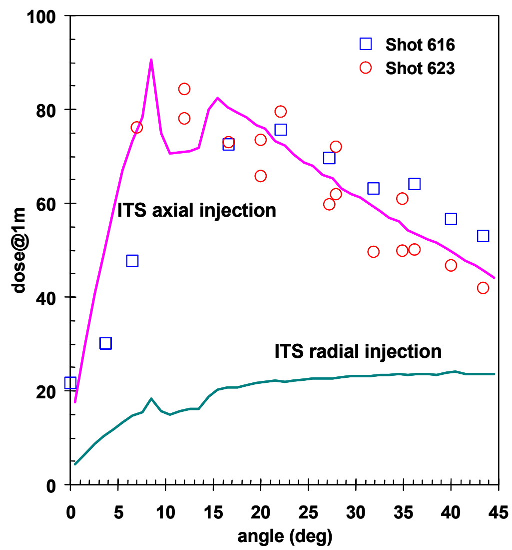

Figure 5. Absolute ITS calculations for axial and radial electron injection compared to measured angular distributions for shots with 5-cm long W insert.

An attempt was made to eliminate x-ray self-absorption in the forward direction by using a hollow-cone anode, illustrated in Fig. 2b, following a reported successful attempt at using a similar cone on Asterix [11]. The voltage and current for this shot were well behaved in a manner similar to shot 623, and the measured on-axis dose was 59 rad @ 1 m. The edge-spread and line-spread functions determined from the rolled-edge measurement are shown in Fig 6. The feature from the 1-mm diam Au tip is clearly seen in the line spread and looks like a 1.74-mm diam uniform disk. The larger diameter may be due to hydro expansion of the tip. The wings outside the central feature are presumably due to electrons impacting the Al cone between the Au tip and the cathode. A significant fraction of the measured dose may be coming from the Al. In retrospect, a 2-mm diam Au tip extending about 3 mm from the end of the cone might help insure that most of the electrons impact Au.

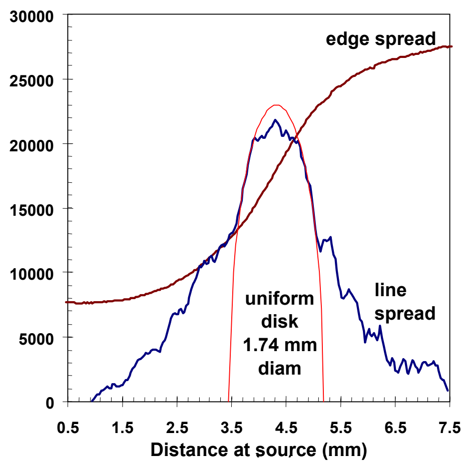

Figure 6. Edge spread and line spread for shot 625 compared to uniform disk.

In conclusion, the RP diode can be coupled effectively to the RITS-3 IVA at 5 MV in negative polarity with the dose produced primarily over a 6-mm long region at the anode tip. Electron deposition on the anode end plate is minimal, but electrons appear to be shed along the side wall, particularly near the outer edge of the knob. In this geometry, which is not optimized for x-ray self-absorption, the dose peaks 20° off axis in a manner consistent with theoretical predictions. The initial use of a hollow-cone anode geometry to minimize self-absorption in the forward direction was partially successful. In contrast, recent experiments on Asterix in negative polarity have used a cone geometry to produce a 2-mm spot (LANL definition) and 70 rads @ 1 m on axis at 4.5 MV [11]. It is not yet clear why the cone geometry works better on negative-polarity ASTERIX (no impedance collapse and smaller spot size) than on RITS-3. Negative polarity RP diode geometries will be further explored on the 6-MV Mercury IVA pulsed-power generator [9] located at NRL.

IV. REFERENCES

[1] S.B. Swanekamp, G. Cooperstein, J.W. Schumer, D. Mosher, F.C. Young, P.F. Ottinger, and R.J. Commisso, "Evaluation of self-magnetically pinched diodes up to 10 MV as high-resolution flash x-ray sources," IEEE Trans. Plasma Sci., vol. 32, no. 5, pp. 2004-2016, 2004.
[2] R.J. Commisso et al., "Overview of the 6-MV, rod-pinch experiment on Asterix," in Proc. 14th IEEE International Pulsed Power Conference (Dallas, TX, June 2003), pp. 479-482, and F.C. Young et al., "Radiographic results for the rod-pinch diode scaled up to 6 MV," ibid., pp. 979-982.
[3] I.D. Smith, V.L. Bailey, J. Fockler, J.S. Gustwiller, D.L. Johnson, J.E. Maenchen, and D.W. Droemer, "Design of a radiographic Integrated Test Stand (RITS) based on a voltage adder, to drive a diode immersed in a high magnetic field," IEEE Trans. Plasma Sci, vol. 28, no. 5, pp. 1653-1659, 2000.
[4] G. Cooperstein, J.R. Boller, R.J. Commisso, D.D. Hinshelwood, D. Mosher, P.F. Ottinger, J.W. Schumer, S.J. Stephanakis, S.B. Swanekamp, B.V. Weber, and F.C. Young, "Theoretical modeling and experimental characterization of a rod-pinch diode," Phys. Plasmas, Vol. 8, pp. 4618-4636, 2001.
[5] R.J. Commisso, G. Cooperstein, D.D. Hinshelwood, D. Mosher, P.F. Ottinger, S.J. Stephanakis, B.V. Weber, and F.C. Young, "Experimental evaluation of a megavolt rod-pinch diode as a radiography source," IEEE Trans. Plasma Sci., Vol. 30, pp. 338-351, 2002.
[6] S.B. Swanekamp, R.J. Allen, R.J. Commisso, G. Cooperstein, D. Mosher, F.C. Young, C. Vermare, J. Delvaux, Y. Hordé, E. Merle, R. Nicolas, D. Noré, O. Pierret, Y.R. Rosol, Y. Tailleur, L. Véron, F. Bayol, A. Garrigues, C. Delbos, G. Nicot, B.V. Oliver, D.V. Rose, and J. Maenchen, "Angular dose variations from 4-6 MV rod-pinch experiments on the Asterix pulsed-power generator," in Proc. 14th IEEE International Pulsed Power Conference (Dallas, TX, June 2003), pp. 483-486.
[7] G. Cooperstein, S.B. Swanekamp, J.W. Schumer, P.F. Ottinger, and R.J. Commisso, "Considerations of rod-pinch diode operation in negative polarity for radiography," in Proc. 14th IEEE International Pulsed Power Conference (Dallas, TX, June 2003), pp. 975-978.
[8] J.R. Threadgold, A.G. Pearce, M.A. Sinclair, and I. Crotch, "Futher work on the implementation of rod pinch diodes on negative polarity pulsed power drivers," Proc. 14th International Conference on High-Power Particle Beams (Albuquerque, NM, 2002), pp. 159-162.
[9] R.J. Allen, C.L. Berry, R.J. Commisso, G. Cooperstein, R.C. Fisher, D.D. Hinshelwood, T.A. Holt, A.T. Miller, D.P. Murphy, J.M. Neri, P.F. Ottinger, D.G. Phipps, J.W. Schumer, S.J. Stephanakis, S.B. Swanekamp, F.C. Young, D.L. Johnson, and I. Smith,, "Initialization and operation of Mercury, A 6-MV MIVA (Magnetically-Insulated Inductive Voltage Adder)," these proceedings.
[10] P.A. Miller and C.W. Mendel, "Analytic model of applied-B ion diode impedance behavior," J. Appl. Phys., vol. 61, pp. 529-539, 1987.
[11] F. Bayol and C. Vermare, private communication.
[12] J.A. Halbleib, R.P. Kensek, G.D. Valdez, S.M. Seltzer, and M.J. Berger, "ITS: the integrated TIGER series of electron/photon transport codes-version 3.0," IEEE Trans. Nucl. Sci., vol. 39, no. 4, pp. 1025-1030, 1992.